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Structure of synoptic-scale waves in the tropical Pacific during July-December 1974-1976

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STRUCTURE OF SYNOPTIC-SCALE WAVES
IN THE TROPICAL PACIFIC
DURING JULY-DECEMBER 1974-1976

Donald Joseph Bepristis

NAVAL POSTGRADUATE SCHOOL

Monterey, California

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DURING JULY-DECEMBER 1974-1976

by

Donald Joseph Bepristis

December 1977

Thesis Advisor: C.-P. Chang

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Structure of Synoptic-Scale Waves in the Tropical Pacific During July-December 1974-1976

by

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I. INTRODUCTION

Various researchers in the past have found evidence that variations in the tropical sea-surface temperature (SST) are associated with changes in the planetary-scale circulation over the tropics (Bjerknes, 1969; Winston and Kruger, 1974, and Namias, 1974). Recently several investigators have concentrated on the years 1972 and 1973 which displayed extremely anomalous and contrasting SST variations in the equatorial eastern Pacific. The 1972 anomaly was the warmest thus far recorded, with the last six month's mean temperature in excess of 2°C above the normal over broad areas. In 1973 the SST pattern was almost completely reversed with the eastern Pacific characterized by anomalies of more than 2°C below normal for the last six month's mean. It was found by Winston and Kruger (1974) that the anomalously warm eastern Pacific SST of 1972 was associated with major changes in the tropical and extratropical planetary scale circulations.

Recently Chang and Miller (1976), Maas (1977) and Delaney (1977) have found that this change in the planetary scale was accompanied by variations in the synoptic-scale tropical disturbances. Delaney's (1977) study involves a cloud cover analysis for the tropical western Pacific during summer and fall of 1972 and 1973. His results indicate that the synoptic-scale waves present during those periods were influenced both by the east-west overturning planetary scale Walker

circulation and by the local effects of SST. Other investigators have also found that variations in tropical wave behavior could be explained in part by the variations of SST and planetary scale flows. According to Chang and Miller's (1976) study of the 1972 and 1973 easterly waves in the tropical Pacific, the differences in vertical wave structure are a result of seasonal variations in the vertical shear of the mean zonal winds, which are directly linked to the east-west SST gradient and the resultant zonal Walker circulation. It was further indicated by Delaney's results that the local wave amplitudes and energetics are strongly dependent on the local variations of the SST.

The purpose of this study is to inquire further into the role of anomalous SST in affecting the synoptic-scale tropical waves. As a first step, the last six months of each year's SST were averaged and deviations from the 1972 to 1976 five-year mean were calculated (Figure 1). These charts cover the entire equatorial Pacific from 10°-20°N for the years 1972 through 1976. The 1972 and 1973 characteristics have already been described by Delaney (1977). The 1975 and 1976 anomaly charts have distinctly different patterns, while the 1974 anomaly pattern is what might be described as "average." The 1975 and 1976 anomalies, although not as intense as 1972 and 1973, are significant in that almost the entire tropical Pacific is covered by cold anomaly in 1975 and warm anomaly in 1976. By analyzing the

tropical synoptic and mean zonal features and their variations with the SST anomalies, it is hoped that more light may be shed on the inter-relationships between them.

II. DATA

A. SEA-SURFACE TEMPERATURE

The SST data used in this study and the earlier study by Delaney (1977) were produced from special monthly SST data charts compiled by the Pacific Environmental Group, National Marine Fisheries Service, for the years 1972 through 1976. These charts contained the average monthly SST for five degree blocks over the entire equatorial and northern Pacific. The data coverage was very good for all areas except the Central Pacific between 180° and 130°W and south of 10°N. For that area data was often sparse or lacking and any analysis over that area should be considred as only tentative. The monthly SST data was averaged over the period of July to December for each year (Figure 2). These five averages were then used to produce a five-year mean chart from which the six-month mean SST anomaly charts were produced.

B. RADIOSONDE DATA

The radiosonde data were obtained from the National Climatic Center and consisted of once daily soundings (00Z) from July to December for 1974, 1975 and 1976, for the six stations shown in Figure 3. In total 184 soundings were used for each station (Koror, Yap, Truk, Ponape, Kwajalein and Majuro), during each year. For the 13 mandatory levels,

meridional and zonal wind components and specific humidities were calculated, and along with temperature they were smoothed over the six month periods using a band pass filter which eliminates variations with periods less than two days or greater than 10 days. The filter eliminates seven days on each end of the six month periods, thus leaving 170 days of filtered data. The filtered meridional wind components were then averaged vertically from 1000 mb to 600 mb and plotted in a time series to facilitate the selection of ridge, trough and maximum northerly and maximum southerly wind occurrences for each station and each period. If a ridge of trough passage falls between two soundings the preceding and following observations were averaged.

Although the number of significant trough passages varied between years and stations, from a low of 32 to a high of 44 (Table I), the average value for each year was 39 passages with a period of 4.4 days.

To describe the average wave structure for each station a compositing technique similar to the one used by Reed et al (1976) was used.

III. RESULTS

A. TIME MEAN FIELDS

1. Sea-Surface Temperature

Figure 1 shows the six-month averaged SST deviations for 1974, 1975 and 1976 from the five year mean (Figure 2). The year 1974 has a less distinctive anomaly pattern and may be considered as a "normal" year. The radiosonde stations studied in this work were either in or near a warm area, but in all cases there was a cold SST anomaly upstream.

The characteristics of each year's SST anomaly and the east-west SST gradient in the western Pacific may be identified by the 28°C isotherm in the actual SST distributions shown in Figure 2. In 1974 the 28°C isotherm is located just at 180° and is nearly north-south across the equatorial Pacific. In 1975 the 28°C isotherm is shifted to the west by more than 20° longitude. This indication of coldness in the eastern Pacific, and concomitant increased east-west SST gradient, are verified by the anomaly chart which shows a cold anomaly over the entire tropical Pacific east of 160°E. The stations from Truk east are all situated downstream from the broad negative anomaly area, whereas the western stations appear to be very close to the zero anomaly line.

In 1976 the 28°C isotherm is shifted eastward to 160°W near the equator, indicating a weakening of the east-west SST gradient there.

The anomaly chart for 1976 shows that south of 10°N along almost the entire equator there was a general warming over the previous two years and that the equatorial region is characterized as greater than 1°C above the mean. In this year the eastern stations in our radiosonde network (Ponape, Kwajalein and Majuro) are in an opposite SST anomaly as compared to 1975, whereas the remaining stations remain near the zero anomaly line.

2. Mean Zonal Wind

The mean zonal winds for 1972 and 1973 as calculated by Chang and Miller show that in 1972, which was an extremely warm SST anomaly year in the eastern Pacific, the upper troposphere is completely dominated by easterlies and that the low levels are predominantly westerlies. In 1973, a very cold SST anomaly year in the eastern Pacific, there was almost a complete reversal of the flow at both the upper troposphere and the surface. The mean zonal winds for 1972 through 1976 are shown in Figure 4. In the central Pacific the 1975 period has a significant increase in the extent of the westerlies in the upper troposphere (near 150 mb) over 1974, while in 1976 this westerly maximum is substantially diminished. At the lower level weak westerlies are evident over the extreme western regions during 1974 and 1976, while in 1975 the surface wind was predominantly easterly.

By examining all five years together the similarities between the two cold SST anomaly years, 1973 and 1975, can be seen, likewise the two warm SST anomaly years differ

only in the eastward extent of the upper level easterlies and the lower level westerlies. It is of interest to note that 1974 falls between the two extremes of warm and cold anomalies as represented by 1972, 1976 and 1973, 1975 respectively.

During 1972, 1974 and 1976 there were also varying degrees of northward and eastward intrusions of the low-level monsoonal trough evident in the western Pacific.

B. TIME AND ZONAL SCALES OF THE WAVES

Using the subjective determinations of trough passage, taken from time series of vertically averaged 1000 mb to 600 mb meridional winds, the time scale and zonal scales of the easterly waves were estimated and shown in Table I. The average number of wave passages at each station for all three years was consistently close to 39, with an average period of 4.4 days and wavelength of 2930 km. This periodicity and wavelength corresponds very well with previous studies by Delaney (1977) and Chang and Miller (1976).

C. COMPOSITES OF WAVE STRUCTURE

Due to the proximity between the two stations and the similar SST environment and resultant wave structure, the composite data for Kwajalein and Majuro (K-M) were combined for all three years. The other stations either had distinct differences in the wave structure or were in different SST regimes, so they will be considered separately to allow for consideration of spatial and temporal variations.

1. 1974

a. Wind Components

The zonal (u) and meridional (v) wind fluctuations of the waves are shown in Figure 5. With the exception of Ponape the maximum u are located near the 200 mb level. At all stations the maximum v are located near 700 mb, and there is an indication that the intensity of the v component increases slowly from east to west.

All the stations show a northeast-southwest horizontal tilt in the lower levels which indicates that u and v are mostly in-phase. However, the vertical tilt, as indicated by the v component from 1000 mb to 300 mb, shifts from eastward at K-M and Truk to nearly vertical at Ponape, and finally westward at Yap and Koror. All the v components except Ponape show a distinct phase reversal near the 300 mb to 250 mb level. At Ponape there is a phase shift above 300 mb but due to the nearly vertical nature of the wave below 300 mb, the shift is not as significant as the other stations.

b. Temperature and Specific Humidity (Figure 6)

All stations, with the exception of Yap and Ponape, show definite warm core structure at the middle-upper troposphere. The temperature composites for both Yap and Ponape suggest very weak warm core systems, possibly reflecting less organized convective activity in the troughs.

The maximum moisture fields tend to be directly above or slightly ahead of the trough at all stations.

The vertical tilt in the moisture field does not appear to correspond to the wave tilt as indicated by the meridional winds, nor is there any consistent pattern of increase or decrease in moisture fluctuations from east to west.

2. 1975

a. u and v Components (Figure 7)

In 1975 again most stations, except Koror and K-M, possess a northeast-southwest tilt in the lower troposphere. Of the two exceptions the implied northwest-southeast tilt above 850 mb at Koror is not felt to be significant due to the very small zonal wind fluctuations.

The zonal wind fluctuations for K-M are comparable in magnitude to those of other stations, and they indicate that K-M may have a north-south to northwest-southeast tilt.

As in 1974 the vertical tilt of the waves is eastward with height at eastern stations; however, unlike 1974 the west stations do not exhibit a westward tilt, but appear nearly vertical up to 300 mb.

The maximum v fluctuation is located consistently at the 850 mb to 700 mb level, but again unlike 1974, there is no indication of amplitude change from east to west.

b. Temperature and Specific Humidity (Figure 8)

Only the westernmost station, Koror, possesses a distinct warm core. Yap indicates a weak warm core in the middle-upper troposphere and Truk, Ponape and K-M all

show weak cold core structures. Of the three eastern stations only Ponape has significant temperature values, and its temperature structure could be interpreted as either weak warm or weak cold core. Taking this into account it is best to describe the waves at stations from Truk eastward as not distinctly organized in their thermal structure.

With the exception of K-M the moisture structure for 1975 appears consistent, with an eastward tilt and the maximum values located at or behind the trough. K-M had a pronounced westward tilt with the maximum moisture found ahead of the trough at 850 mb.

3. 1976

a. u and v Components (Figure 9)

As in 1974 all stations in 1976 have a well defined northeast-southwest tilt. The intensities of the meridional winds are significantly greater at Truk and Ponape, with the maximum value located at 175-150 mb. The zonal wind maximum appears consistently located at the 700-600 mb level and all of the stations have virtually the same intensity.

Unlike the previous two years, there is no indication of change in the vertical wave tilt from east to west. The stations from Truk westward show a phase reversal in the zonal winds above 300 mb; below that they are nearly vertical. Ponape and K-M remain vertical from 1000 mb up to 175 mb and only show a slight phase shift above that.

b. Temperature and Specific Humidity (Figure 10)

K-M and Yap both possess distinct and well defined warm cores at the 400 mb to 250 mb levels. The remainder of the stations are characterized by indistinct temperature structures. Koror and Ponape appear as weak warm core systems; whereas Truk appears to be weak cold core.

Although K-M and Yap have similar thermal structures, their moisture distributions are completely dissimilar. Yap has its maximum moisture directly over the trough, as would be expected from a well developed warm core system, and K-M's maximum moisture is behind the trough and almost directly over the maximum southerly winds. The other three stations, which had indistinct thermal structures, all had their maximum moisture located upstream of the trough and tilting westward above 700 mb.

IV. DISCUSSION AND CONCLUSIONS

The main findings of this study may be summarized as follows:

1) The average wave period and wavelength for each year are relatively constant, at 4.4 days and 2930 km, respectively.

2) Except for Majuro in 1975 all stations for all three years have a definite northeast-southwest meridional tilt in the lower troposphere.

3) With the exception of 1976, the vertical tilt of the waves, as indicated by the phase shift between the 1000 mb to 500 mb levels, shifted from 1/2 cycle westward at the eastern stations to near vertical or 1/4 cycle eastward at the westernmost stations. The waves during 1976 showed little indication of tilt at all stations.

4) There are significant variations in the wave thermal structure during the entire study period.

To understand better the relationship between wave tilt and mean zonal wind, a graph was constructed with vertical tilt in cycles as the abscissa, and the station 150 mb mean zonal wind value as the ordinate (Figure 11a). The data for this plot covers 1972 to 1976 and yields a correlation coefficient of .71; thus, there appears to be a positive correlation between the vertical wave tilt and the background zonal flow. This also indicates that the waves

adjust rapidly to the mean flow as they propagate from east to west.

From the mean zonal wind data the ascending branch of the Walker circulation for the various years can be discerned from the regions of upper tropospheric divergence. Of the five years analyzed, 1973 exhibits the westernmost location of the ascending branch and 1972 the easternmost location, while 1974 through 1976 show variations between these two extremes. Because the Walker circulation seems to be related to the east-west SST gradient, it can be seen that the vertical tilt of the wave is indirectly influenced by the SST variations in the eastern Pacific via the Walker circulation.

Chang and Miller (1977) proposed that warm SST typically found in the western Pacific may result in more thermally driven "warm core" energetics, which would result in the wave vertical structure being less effected by the basic zonal flow. For 1976 this premise was partly substantiated. There was very little or not vertical tilt exhibited from east to west; however, the expected thermal structure was not well defined. To help determine what effect SST does have on the thermal structure of easterly waves, the averaged temperature difference between trough and ridge at the upper-middle tropospheric layer of 250-400 mb was plotted against the station SST. For this plot the correlation coefficient is -0.21. If the average SST at 10° longitude upstream is used instead of the local SST, the correlation coefficient becomes 0.29 (Figure 11b). If the correlation

coefficient is recalculated deleting the two easternmost stations, Kwajalein and Majuro, the correlation more than doubles to 0.60. These results indicate that the thermal structure of the waves was more influenced by the upstream SST than the local SST.

The adverse effects of Majuro and Kwajalein on the calculations suggests that the waves in the eastern-central Pacific may be instigated by mechanisms other than thermal forcing and have not undergone sufficient influence of latent heat release to become thermally driven by the time they passed Majuro and Kwajalein. As the waves continue westward the increased correlation suggests that the continued exposure to increasing SST enhances the convective activity and latent heating.

There appears to be reasonable evidence that variations in the tropical SST do effect both the large-scale and synoptic-scale features in the tropical Pacific. To determine sufficiently the extent that the thermal structure and energetics of the tropical easterly waves are influenced or modified by the local and large-scale SST variations, a more extensive data study should be undertaken. This would depend on both the expansion of data coverage from the present network and improved data quality.

TABLE I. Time and zonal scale of the waves. Numbers indicate number of waves passing indicated stations during 1974, 1975 and 1976.

	KOROR	YAP	TRUK	PONAPE	KWAJ.	MAJURO	AVERAGE WAVE NO.	PERIOD	WAVE-LENGTH
1974	39	36	41	40	36	40	38.6	4.4 days	2930 km
1975	40	37	43	44	32	38	39.0	4.4 days	2930 km
1976	37	41	36	43	38	36	38.5	4.4 days	2930 km

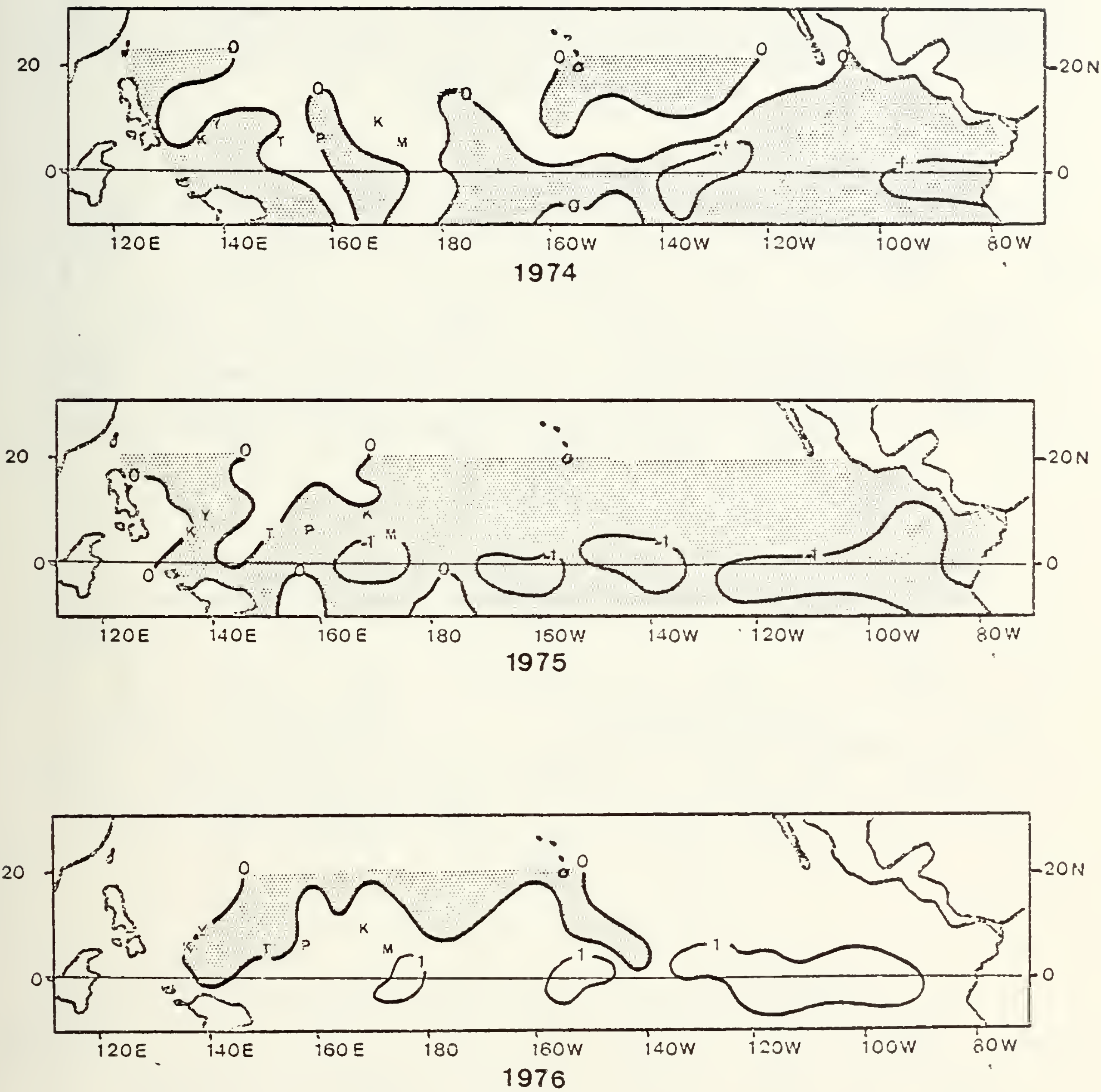

Fig. 1. Sea-surface temperature anomalies (^{O}C) for 1974, 1975 and 1976 taken from 5-year mean.

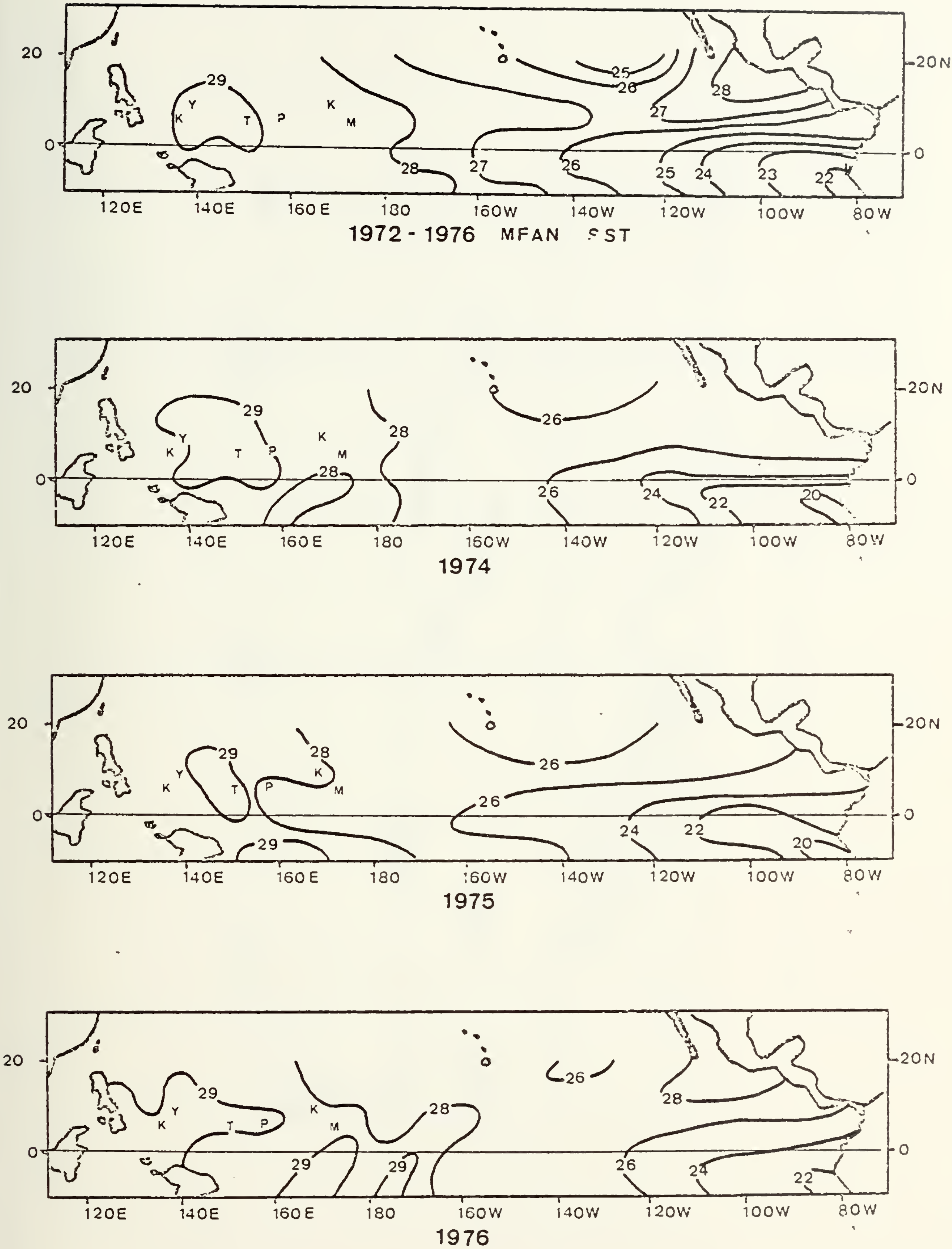

Fig. 2. Sea-surface temperature (^{o}C) for 1974 through 1976 and 1972-1976 mean.

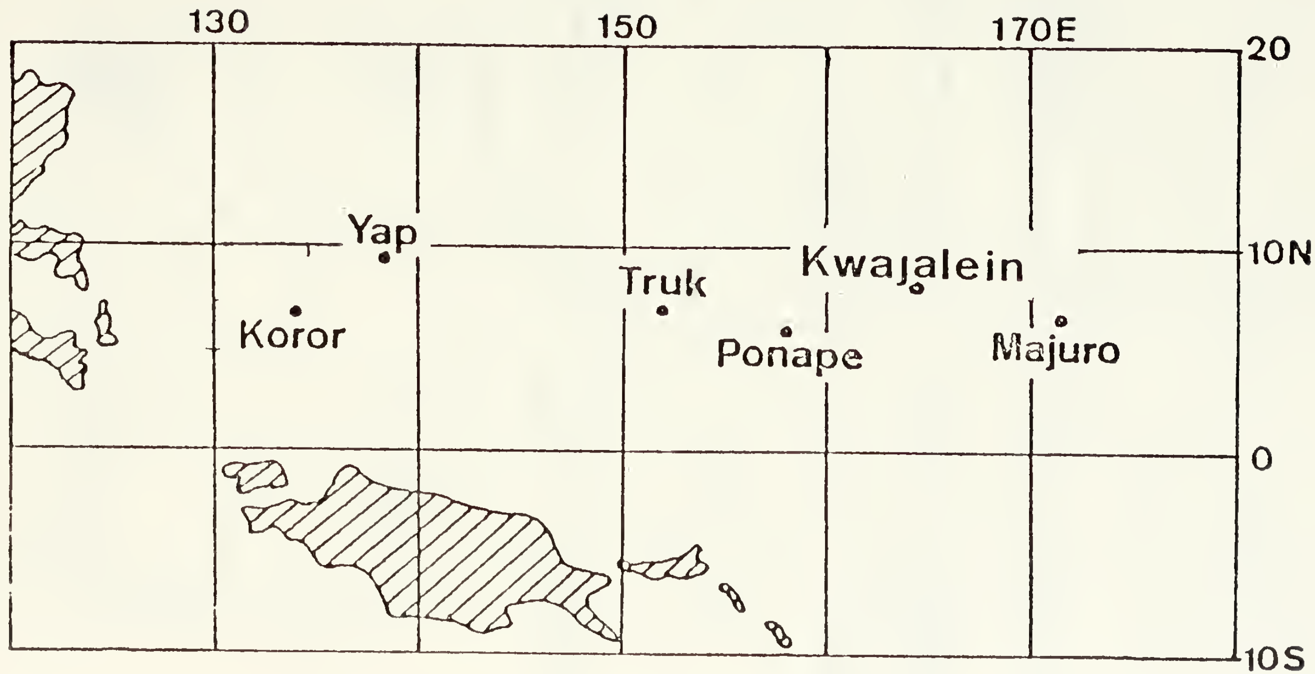

Fig. 3. Radiosonde stations used in study.

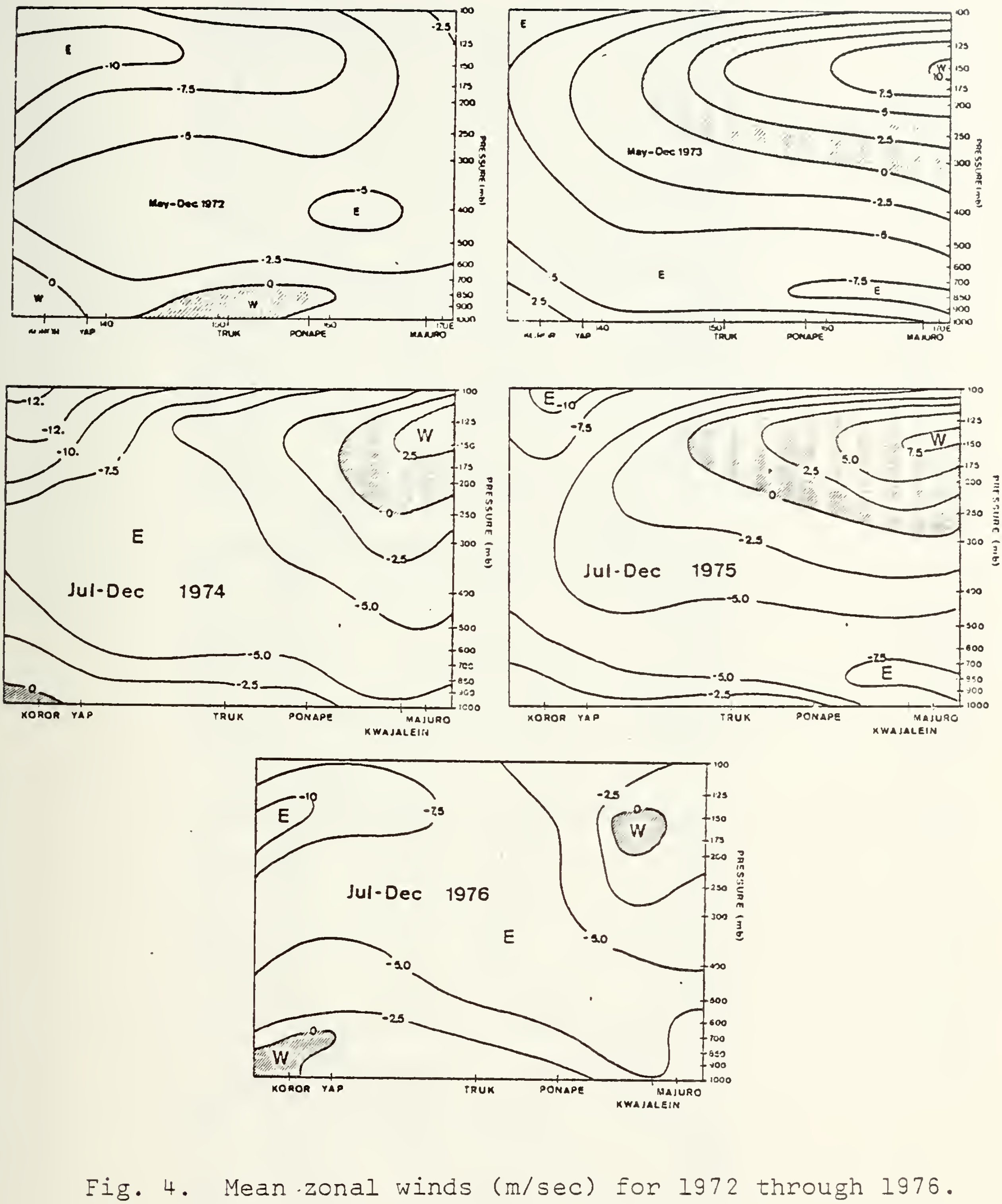

Fig. 4. Mean zonal winds (m/sec) for 1972 through 1976.

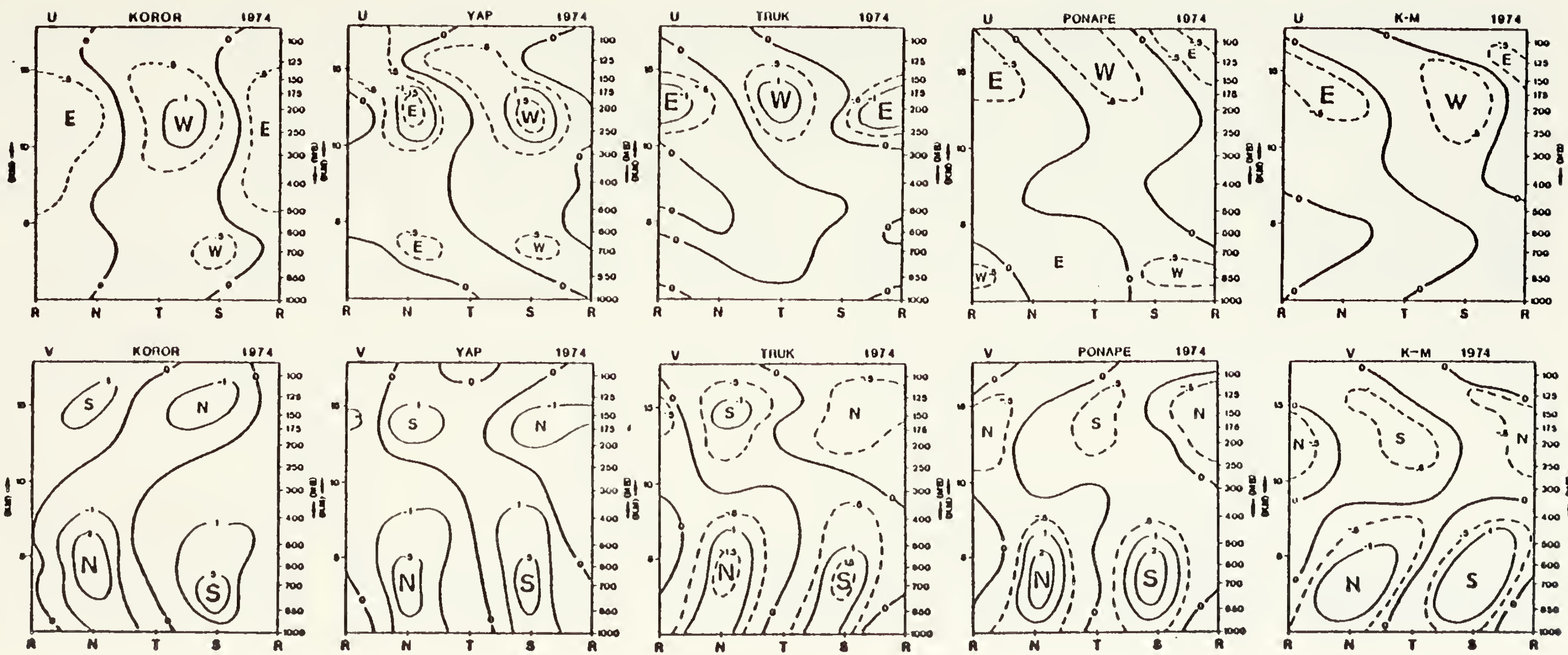

Fig. 5. Composite vertical wave structure of u and v component winds (m/sec) during 1974 for the indicated stations.

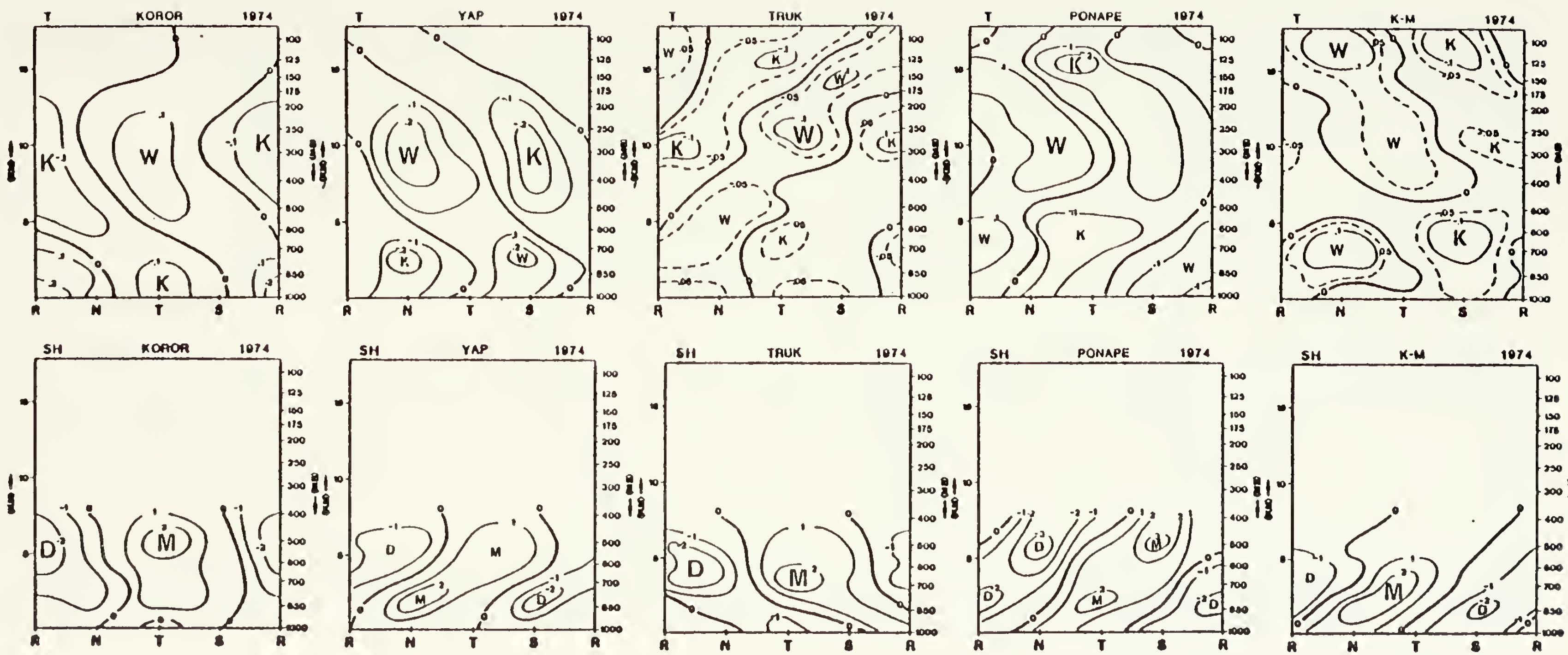

Fig. 6. Composite vertical wave structure of temperature (^{o}C) and specific humidities (gm/kgx10) during 1974 for the indicated stations.

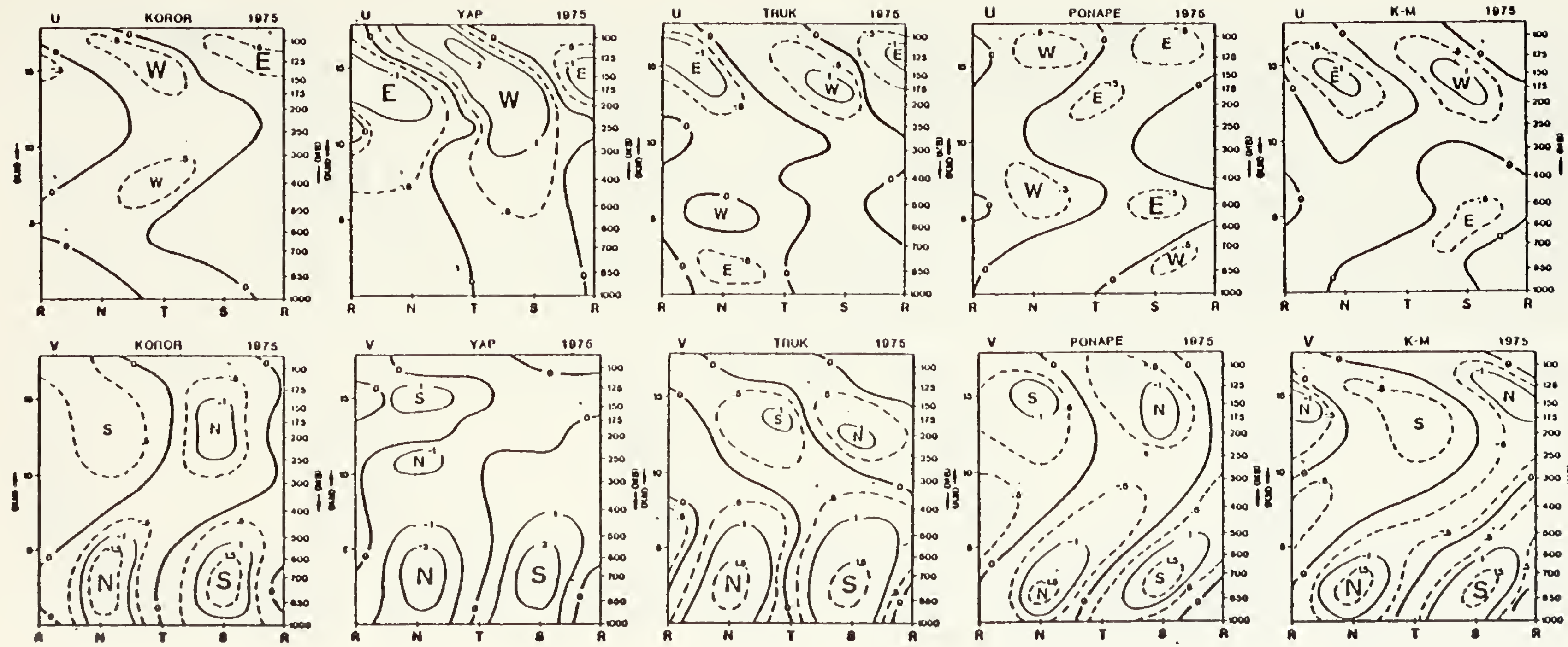

Fig. 7. Composite vertical wave structure of u and v component winds (m/sec) during 1975 for the indicated stations.

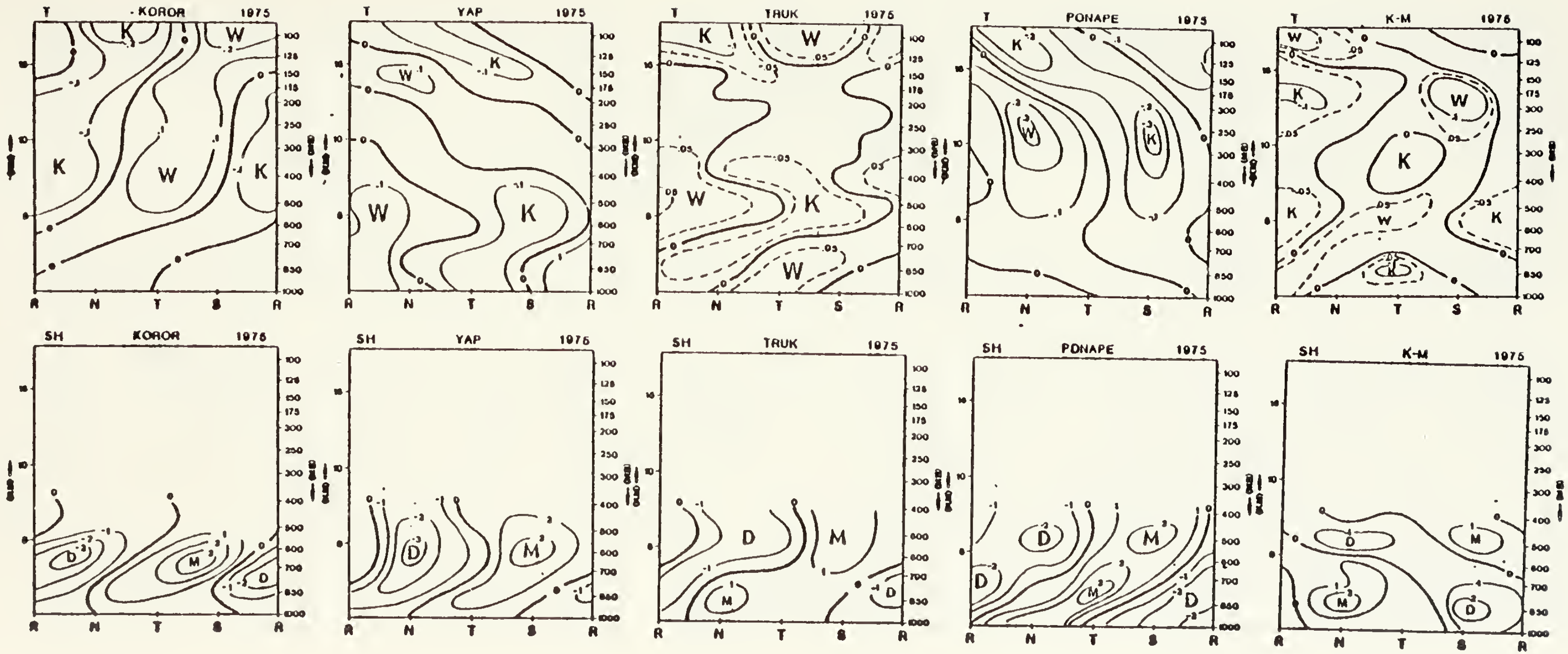

Fig. 8. Composite vertical wave structure of temperature (^{O}C) and specific humidities (gm/kgx10) during 1975 for the indicated stations.

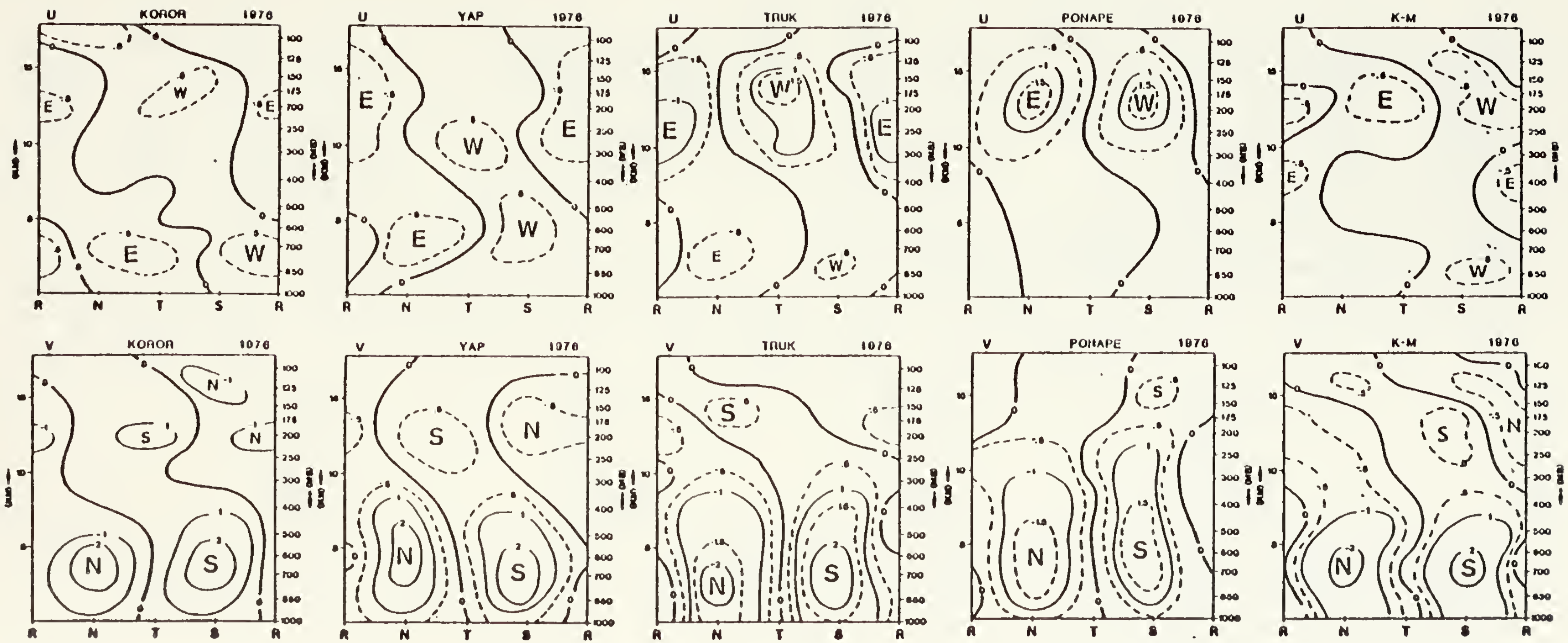

Fig. 9. Composite vertical wave structure of u and v component winds (m/sec) during 1976 for the indicated stations.

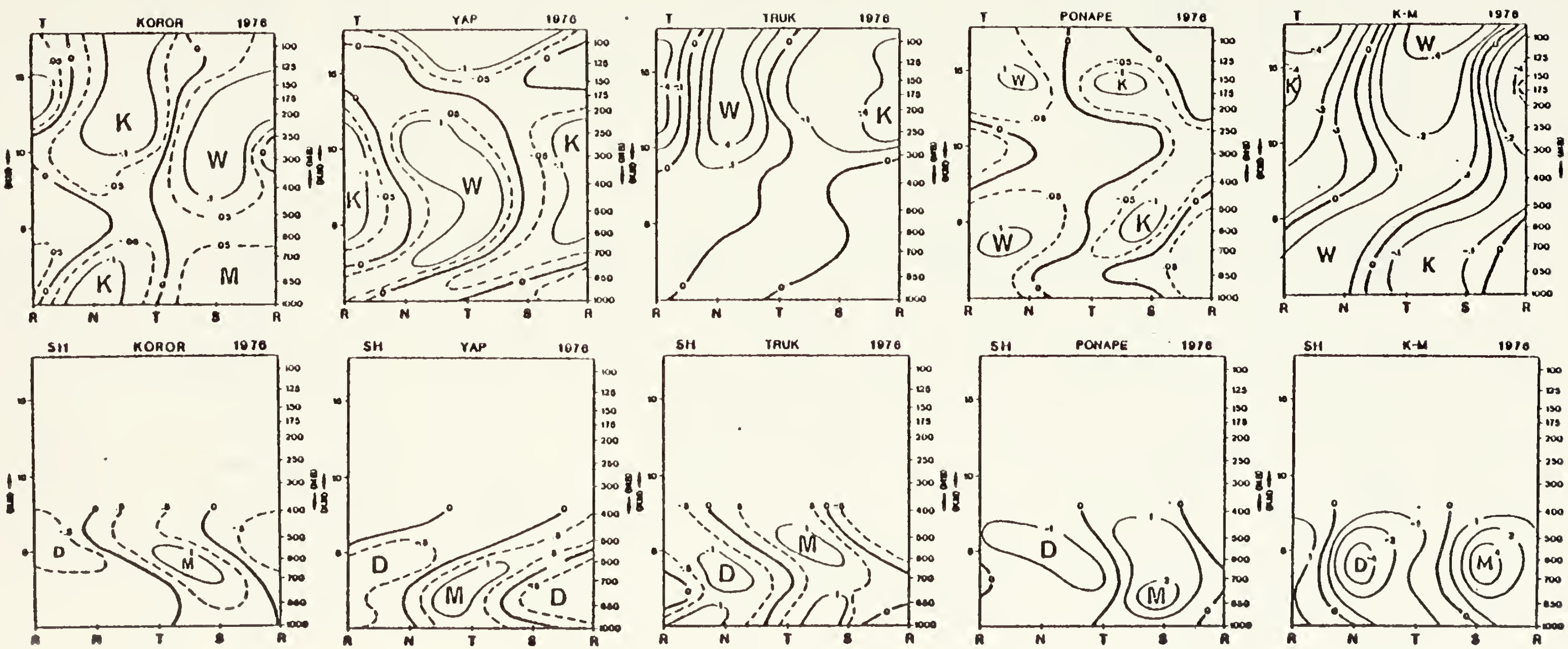

Fig. 10. Composite vertical wave structure of temperature (^{o}C) and specific humidities (gm/kgx10) during 1976 for the indicated stations.

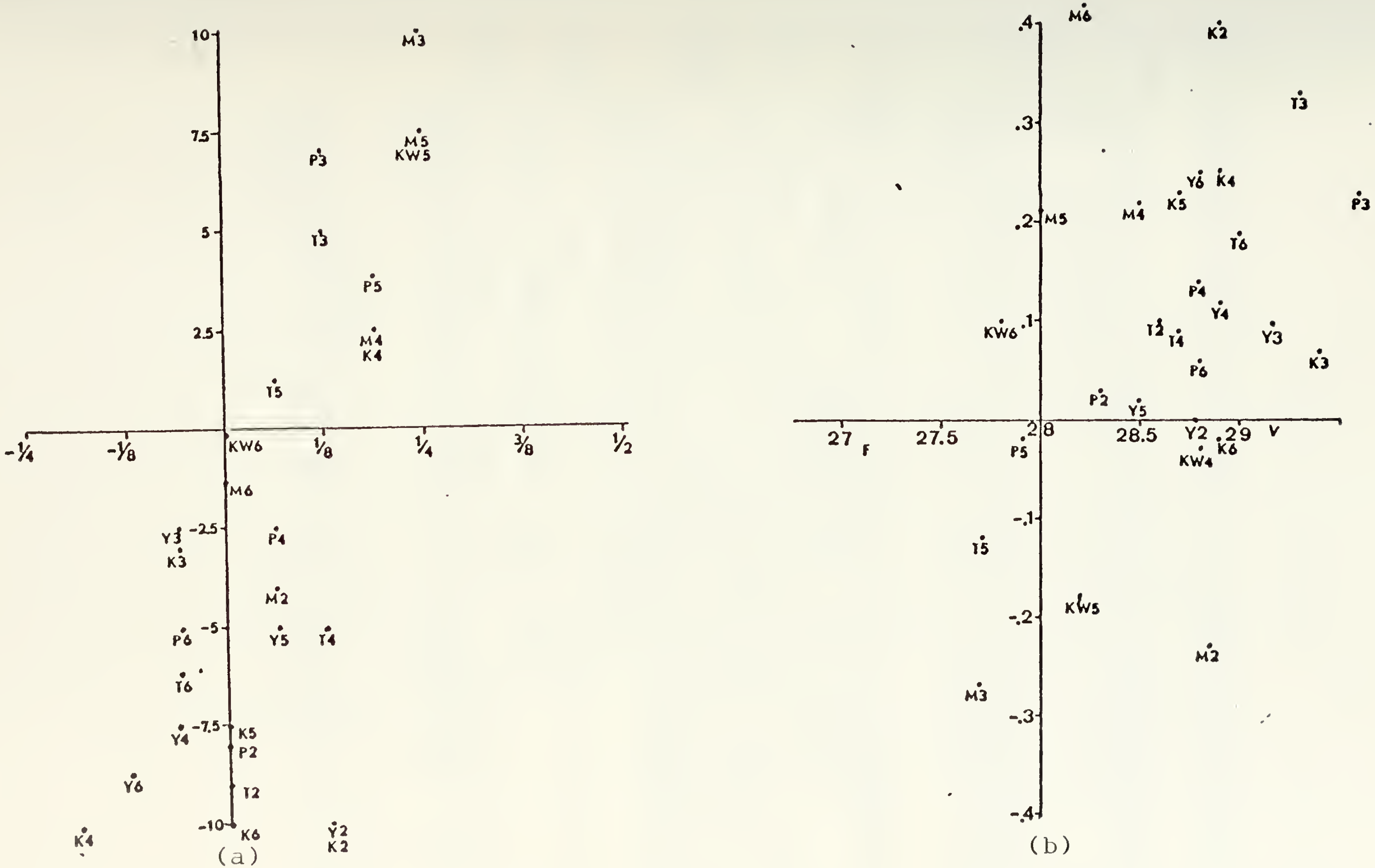

Fig. 11. (a) Plot of 150 mb wind (m/sec)(ordinate) vs. 1000-500 mb vertical phase shift (abscissa) for 1972-1976. Station and year indicated by letter and number, i.e. M5 is Majuro 1975. (b) Plot of average 250-400 mb trough temperature (^{o}C) (ordinate) vs. average 10^{o} upstream SST (^{o}C) (abscissa).

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